

Electron-positron pair production near the Galactic Centre and the 511 keV emission line

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ABSTRACT

Recent observations indicate that a high production rate of positrons (strong 511 keV line) and a significant amount of excess GeV gamma-ray exist in our Galactic bulge. The latter issue can be explained by ~ 40 GeV dark matter annihilation through $b\bar{b}$ channel while the former one remains a mystery. On the other hand, recent studies reveal that a large amount of high density gas might exist near the Galactic Centre million years ago to account for the young, massive stars extending from 0.04 pc - 7 pc. In this article, I propose a new scenario and show that the 40 GeV dark matter annihilation model can also explain the required positron production rate (511 keV line) in the bulge due to the existence of the high density gas cloud near the supermassive black hole long time ago.

Key words: Dark matter

1 INTRODUCTION

In the past few decades, a flux of 511 keV photons $\phi_{511} \sim 10^{-3}$ ph cm $^{-2}$ s $^{-1}$ emitted in the Milky Way was reported (Leventhal, MacCallum and Stang 1978; Knödseder et al. 2005). These 511 keV photons are supposed to originate from the positrons produced. The predicted production rate of positrons in the bulge and disk are respectively given by $\dot{N}_{e+} = 11.5_{-1.44}^{+1.8} \times 10^{42}$ s $^{-1}$ and $\dot{N}_{e+} = 8.1_{-1.4}^{+1.5} \times 10^{42}$ s $^{-1}$ (Prantzos et al. 2011; Perets 2014). In particular, the bulge to disk ratio is abnormally high $B/D = 1.42_{-0.30}^{+0.34}$ (Prantzos et al. 2011; Perets 2014). The positrons produced in the Galactic disk can be explained by some mechanisms, such as novae, supernovae, pulsars and low-mass X-ray binaries (LMXB) (Prantzos et al. 2011). However, the high positron production rate in the bulge remains a mystery, especially at the central part. Observations indicate that the 511 keV line comes from mainly diffuse sources rather than point sources (Cesare et al. 2006). It has been suggested that the positrons produced through dark matter annihilation can account for the required production rate (Boehm et al. 2004). For example, Ascasibar et al. (2006) show that dark matter annihilation can give enough positrons, and the dark matter mass should be smaller than 100 MeV if the annihilation cross section is velocity-independent. Later, based on the gamma-ray spectral shape, Sizun et al. (2006) further constrain the dark matter mass to smaller than 7.5 MeV. Although these models can give enough positrons to account for the 511 keV line, we do

not have another independent promising observational evidence to support these models. Also, most of the models depend strongly on the dark matter density profile, annihilation cross-section and the dark matter annihilation channels.

Recently, an excess of GeV gamma-ray near the Galactic Centre has been reported (Goodenough and Hooper 2009; Hooper and Goodenough 2011; Gordon and Macias 2013; Abazajian et al. 2014; Daylan et al. 2014). The spectrum obtained can be best fitted with the annihilation of dark matter particles with mass $m \sim 40$ GeV through $b\bar{b}$ channel. The required annihilation cross-section $\langle \sigma v \rangle$ is about $(1 - 7) \times 10^{-26}$ cm 3 s $^{-1}$ (Abazajian et al. 2014; Daylan et al. 2014), which is consistent with the expected canonical thermal relic abundance cross-section $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm 3 s $^{-1}$ in cosmology. Based on this result, Boehm et al. (2014) try to use this model to explain the 511 keV line. However, the production rate is too small to account for the required rate (Boehm et al. 2014).

In this letter, I suggest a possible mechanism to account for both the 511 keV line and the GeV gamma-ray excess. By assuming the existence of a large dense cloud near the supermassive black hole $\sim 10^6$ years ago and following the model that used to account for the GeV gamma-ray excess, the production rate of positrons can satisfy the required rate.

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2 THE DENSE CLOUD NEAR THE SUPERMASSIVE BLACK HOLE

Recent studies indicate that a large amount of dense gas $\sim 10^5 M_\odot$ in the form of a disk might exist near the Galactic Centre ($r \leq 0.4$ pc) $10^{6.5}$ years ago to account for the young, massive stars extending from 0.04 pc - 0.4 pc (Wardle and Yusef-Zadeh 2012; Lucas et al. 2013; Wardle and Yusef-Zadeh 2014). The existence of the dense gas can overcome tidal shear in the vicinity of the supermassive black hole and help to explain the truncation of the stellar surface density within 0.04 pc. Part of the cloud is converted to stars and the remainder is accreted onto the supermassive black hole (Wardle and Yusef-Zadeh 2014). The accretion can last for $\sim 10^{14}$ s, and the number density of the cloud can be as high as $n_g \sim 10^{10} \text{ cm}^{-3}$ (Wardle and Yusef-Zadeh 2014). Most particles in the gas are electrically neutral because the temperature is not enough for ionization (Wardle and Yusef-Zadeh 2014). Furthermore, recent studies also indicate that the density of gas was $n_g \sim 2 \times 10^8 \text{ cm}^{-3}$ at 1 pc from the Galactic Centre million years ago to overcome tidal shear (Yusef-Zadeh et al. 2015). The size of such a high density region is probably larger than 5 – 7 pc (Goicoechea et al. 2013; Yusef-Zadeh et al. 2015).

In the following, I propose that a large amount of positrons can be produced in the dense gas through pair-production mechanism ($\gamma \rightarrow e^+ + e^-$). If the photons produced by dark matter annihilation have energy greater than $2m_e c^2$, pair-production is possible in the field of the nucleus from the surrounding gas. The pair-production cross-section for photon energy greater than 0.1 GeV is $\sigma_{pp} \approx 9 \times 10^{-27} \text{ cm}^2$ (Longair 1994), and it would be smaller for lower energy. Although this cross-section is small, the amount of positrons produced would still be large if the number of gas nuclei is large.

Therefore, when a large amount of gamma-ray produced by dark matter annihilation is passing through this dense cloud of gas, a large amount of positrons can be produced. The positrons produced can also generate secondary photons by bremsstrahlung process. These photons produced can further produce high-energy positrons. As a result, cascades of electrons, positrons and photons would be produced. Assume that the mean density and the size of the dense cloud are $n_g \sim 10^8 \text{ cm}^{-3}$ and $R \sim 5$ pc respectively. The optical depth of the electron-positron pair-production is $\tau \approx n_g \sigma_{pp} R \sim 13$. If we assume that the gas cloud density is falling with distance $n_g \propto 1/r^3$ (Yusef-Zadeh et al. 2015), the optical depth is $\tau = \int_{0.4 \text{ pc}}^5 \text{pc} n_g \sigma_{pp} dr \approx 17$. For $\tau = 13 - 17$, each high-energy photon entering the cloud would generate ~ 1000 positrons in the pair-production mechanism (Longair 1994). The pair-production rate is efficient when the photon energy is greater than 0.1 GeV.

Since the optical depth is large, the energy of the final positrons produced would be $E \approx 2m_e c^2 \approx 1 \text{ MeV}$ (still relativistic). This satisfies with the strong constraints on higher energy positrons from in-flight annihilations ($E \leq 3 \text{ MeV}$) (Beacom and Yüksel 2006). When the positrons leave the dense cloud, they would cool down mainly by synchrotron loss, inverse Compton scattering, bremsstrahlung loss and coulomb loss (Longair 1994; Storm et al. 2013):

$$b(E) = b_s \gamma_e^2 + b_i \gamma_e^2 + b_h n_H \left(\frac{E}{1 \text{ eV}} \right) + b_e n_e \left[1 + \frac{\ln(\gamma_e/n_e)}{75} \right], \quad (1)$$

where $b_s = 6.6 \times 10^{-14} \text{ eV/s}$, $b_i = 6.5 \times 10^{-15} \text{ eV/s}$, $b_h = 3.7 \times 10^{-16} \text{ eV/s}$, $b_e = 6.1 \times 10^{-7} \text{ eV/s}$, n_H is the number density of hydrogen atom in cm^{-3} , n_e is the electron number density in cm^{-3} , and γ_e is the Lorentz factor of a positron. Here, we assume that the magnetic field strength in the Galactic bulge is of the order $B \sim 10^{-5} \text{ G}$ (Muno et al. 2004).

The survival probability of positrons before forming positroniums is (Prantzos et al. 2011)

$$P(E, E_f) = 1 - \exp \left[-n_e \int_{E_f}^E \frac{v(E') \sigma_a(E') dE'}{b(E')} \right], \quad (2)$$

where σ_a is the annihilation cross-section and E_f is the final energy of positrons after cooling. In order to form positronium, a positron should cool down to lower than 100 eV. For $E = 1 \text{ MeV}$, $E_f = 100 \text{ eV}$ and $n_e \sim 0.1 \text{ cm}^{-3}$ near the Galactic Centre, only less than 1% of positrons would annihilate with electrons before forming positroniums. Fig. 1 shows that our model satisfies the constraint of MeV photon spectrum observed (Beacom and Yüksel 2006). A relativistic positron can cool down to non-relativistic in $\sim 10^{13} \text{ s}$ if the injection energy is $\sim 1 \text{ MeV}$ (see Fig. 2). This means that the positrons produced $\sim 10^{14} \text{ s}$ ago by pair-production mechanism in the dense gas would use $\sim 10^{13} \text{ s}$ to cool down to non-relativistic. Then they would combine with hydrogen atoms to form positroniums and emit 511 keV line. Basically, since we can still observe the strong 511 keV line nowadays, the cooling time scale t_c should be less than the time of existence of the gas cloud t_e . Moreover, the cooling time scale should be longer than the timescale of disappearance of the gas cloud t_a (the duration between the present time and the moment of the disappearance of the gas cloud). Based on our calculations, the condition $t_e > t_c$ is satisfied. However, since t_a is hard to confirm, we assume that $t_e > t_a$ in the following discussion.

In fact, the positrons produced in the dense cloud would finally be trapped by the magnetic field to within 100 pc (Beacom and Yüksel 2006). In other words, the 511 keV line signal produced by these positrons would only extend to 100 pc from the Galactic Centre, which seems inconsistent with the morphology observed ($\sim 1 \text{ kpc}$ in size) (Knödseder et al. 2005). Nevertheless, the 511 photon flux from the outer part of Galactic bulge ($\geq 100 \text{ pc}$) can be explained by the morphology of LMXRB ($\phi_{511} \approx 2 \times 10^{-3} \text{ cm}^{-2} \text{ s}^{-1} \text{ rad}^{-1}$) (Bird et al. 2007; Weidenspointner et al. 2008; Prantzos et al. 2011). Our model is going to account for the unexplained strong 511 keV line from the central part of Galactic bulge ($\phi_{511} \approx 6 \times 10^{-3} \text{ cm}^{-2} \text{ s}^{-1} \text{ rad}^{-1}$).

The rate of dark matter annihilation within a radius R is given by

$$\dot{N}_{DM} = \int_0^R \frac{\rho_{DM}^2}{m^2} < \sigma v > 4\pi r^2 dr, \quad (3)$$

where

$$\rho_{DM} = \rho_\odot \left(\frac{r}{r_\odot} \right)^{-\gamma} \left[\frac{1 + (r/r_s)^\alpha}{1 + (r_\odot/r_s)^\alpha} \right]^{-(\beta-\gamma)/\alpha}. \quad (4)$$

Following Cirelli, Serpico and Zaharijas (2013), we take

$\rho_\odot = 0.3 \text{ GeV/cm}^3$, $r_\odot = 8.5 \text{ kpc}$, $r_s = 20 \text{ kpc}$, $\alpha = 1$, $\beta = 3$ and $\gamma = 1.26$ (the best-fit value to account for the GeV excess). By using Eq. (3) and assuming $\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$, the dark matter annihilation rate within 5 pc is $\dot{N}_{DM} = 8 \times 10^{37} \text{ s}^{-1}$. By using the spectrum calculated in Cembranos et al. (2011), the total number of photons produced with energy greater than 0.1 GeV through dark matter annihilation is 115 per one annihilation (see Fig. 3). Assuming $\tau = 13$, the total number of positrons produced in this pair-production mechanism within 5 pc is $\sim 10^{43} \text{ s}^{-1}$, which is enough to account for the 511 keV line.

On the other hand, the diffuse source of positrons produced directly from dark matter annihilation can be estimated by using the positron energy spectrum obtained from Borriello et al. (2009) (see Fig. 4). The total number of positrons produced per one annihilation is 12. By using Eq. (3), $\dot{N}_{DM} \sim 10^{39}$ for $R = 1 \text{ kpc}$. Therefore, the rate of diffuse positron production within 1 kpc is about 10^{40} s^{-1} . This minor diffuse source of positrons requires a bit longer time to cool down to non-relativistic (see Fig. 2). They would finally contribute to the 511 keV line which extend to 1 kpc from the Galactic Centre. However, this minor diffuse source is negligible compared with the other available explanations.

The rate of change of total number of positrons in the bulge is given by

$$\frac{dN_{e+}}{dt} = \dot{N}_{e+} - N_{e+} n_H \sigma_{eH} v, \quad (5)$$

where σ_{eH} is the cross-section of positronium production. Since the energy dependence of the cross-section is an exponential function of the positron energy, the positronium formation rate would be the largest for certain positron energy ($\sim 14 \text{ eV}$) (Boehm et al. 2014). As a result, a dynamical equilibrium state would be achieved when the positrons are cooled to around 14 eV and become positroniums. In equilibrium, the total number of cooled positrons in the bulge is $N_{e+} \sim 10^{50}$ because $\dot{N}_{e+} \sim 10^{43} \text{ s}^{-1}$ and $n_H \sigma_{eH} v \sim 10^{-7} \text{ s}^{-1}$. However, part of the dense cloud would eventually change to stars, and most of the remaining part would be captured by the supermassive black hole. Therefore, the relatively strong 511 keV line would not last forever. When the dense cloud disappears, the production rate would reduce to $\dot{N}_{e+} \sim 10^{42} \text{ s}^{-1}$ (from novae, supernovae, pulsars, LMXRB, etc.). Also, the final batch of positrons produced from the dense cloud would diffuse away and cool down to form positroniums to give 511 keV line. As a result, from the solution of Eq. (5), the total number of positrons would decrease significantly at t_c after the disappearance of the dense cloud:

$$N_{e+} = \frac{\dot{N}_{e+}}{n_H \sigma_{eH} v} (1 - e^{-n_H \sigma_{eH} v t}) + N_{e+0} e^{-n_H \sigma_{eH} v t}, \quad (6)$$

where $N_{e+0} \sim 10^{50}$ is the original number of positrons, and t is the time after all the positrons produced from the dense cloud disappeared. When $t \gg 10^7 \text{ s}$, the total number of positrons in the bulge would reduce to $N_{e+} \sim 10^{49}$, and the intensity of the 511 keV line would decrease by a factor of three. In Fig. 5, we show the changes of positron number, gas cloud density and the strength of 511 keV flux as a function of time.

3 DISCUSSION AND CONCLUSION

In this letter, we discuss a possible model to explain the observed 511 keV line. Following the dark matter annihilation scenario that used to account for the GeV gamma-ray excess in the Galactic Centre, the gamma-ray produced by the dark matter annihilation can generate enough positrons ($\sim 10^{43} \text{ s}^{-1}$) through electron-positron pair-production inside the dense cloud, if we assume the existence of a dense gas cloud surrounding the supermassive black hole 10^{14} s ago. The cooling time scale (diffusion time scale) of positrons is $t_c \sim 10^{13} \text{ s}$. Therefore, the strong 511 keV line observed is just a single event, which last for about $\sim 10^{13} \text{ s}$ after the disappearance of the dense cloud.

However, the uncertainties in the cloud size and density may significantly affect the optical depth for pair-production. Our model would fail if the optical depth near the supermassive black hole is too small for the high-energy gamma-ray. Therefore, more observational data from the parsec region near the supermassive black hole is needed to verify our proposed model. To conclude, by assuming a large dense cloud with number density $\sim 10^8 \text{ cm}^{-3}$, it can generate enough positrons to account for the 511 keV line and explain the excess GeV gamma-ray observed in the Galactic Center.

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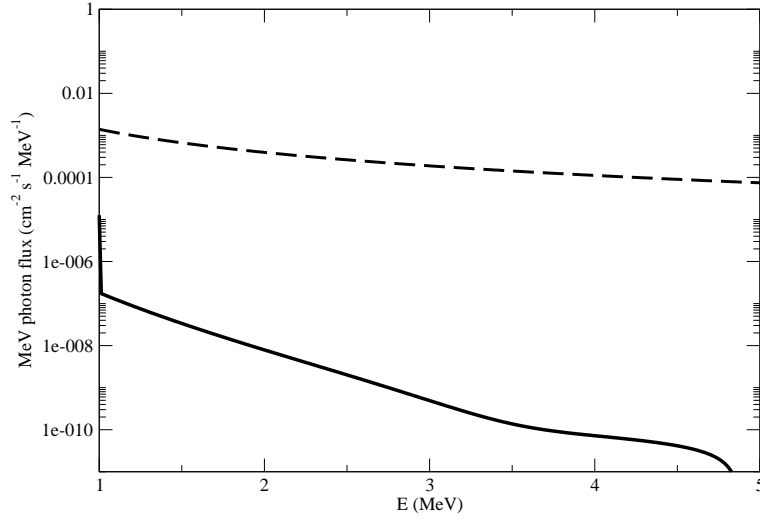


Figure 1. The solid and dashed lines represent the MeV photon spectrum due to positron-electron annihilation after passing through the dense cloud and the observed MeV photon spectrum respectively (Beacom and Yüksel 2006).

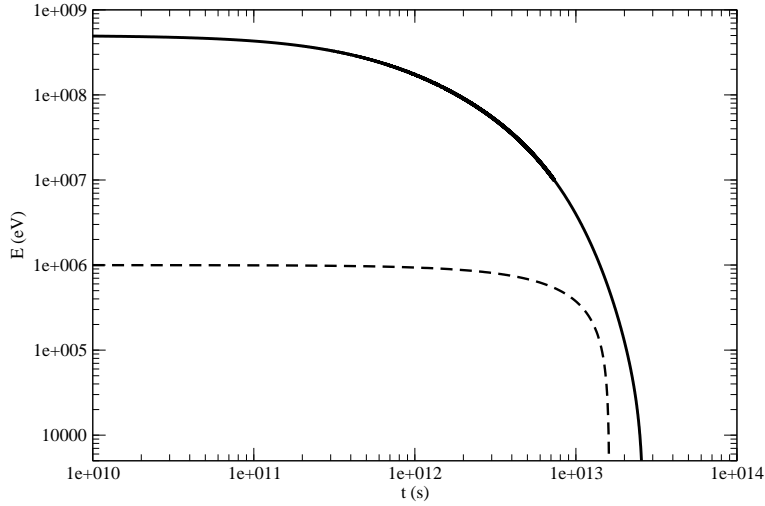


Figure 2. The cooling of a 1 MeV positron (dashed line) and a 0.5 GeV positron (solid line).

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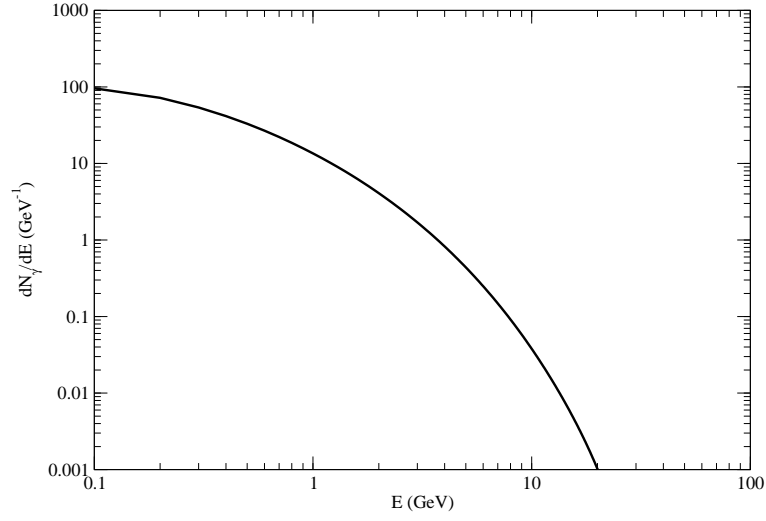


Figure 3. The photon spectrum per one dark matter annihilation (Cembranos et al. 2011). Here, we assume $m = 40 \text{ GeV}$.

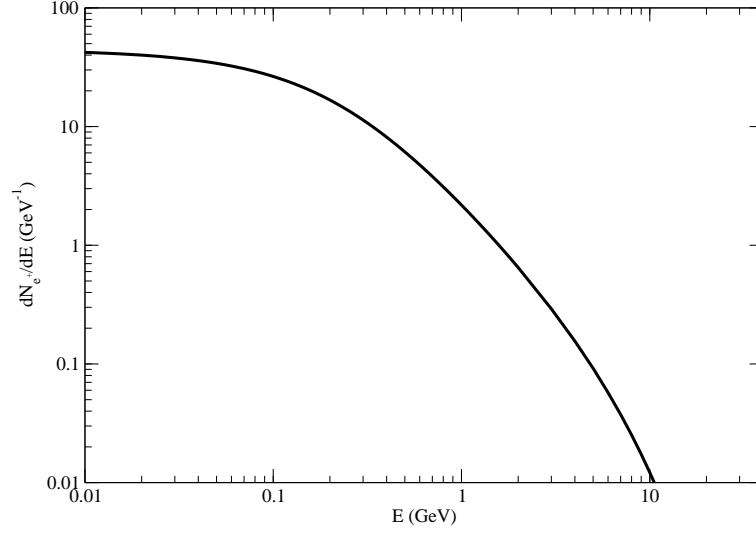


Figure 4. The positron spectrum per one dark matter annihilation (Borriello et al. 2009). Here, we assume $m = 40 \text{ GeV}$.

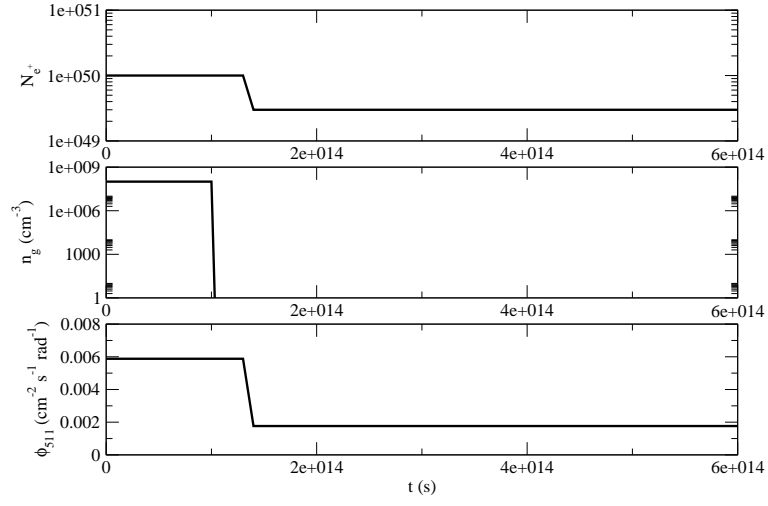


Figure 5. The changes of positron number, gas cloud density and the strength of 511 keV flux as a function of time. Here, we assume that the time of existence of the gas cloud t_e and the cooling time scale for positrons t_c are 10^{14} s and 2×10^{13} s respectively.